A Case Study of Modal Mass Acceleration Curve Loads vs. Sine Loads

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Introduction

- Per JPL 30 years of experience, Modal Mass Acceleration Curve (MMAC) approach bounds Coupled Loads Analyses (CLA) results while not being overly conservative. However, most spacecraft industries use sine loading.
  - *JPL Past Projects supported by MMAC:*
    - Galileo (1989), SIR-C (1994), Cassini (1997), Deep Space 1 (1998), SRTM (2000), MER (2003), MSL (2011),SMAP (2015)
  - *JPL On-going Projects supported by MMAC:*
    - M2020 (2020), Europa (2020s), NISAR (2020)

- The purpose of this study is to compare the MMAC and sine analyses results, against CLA results.
  - Per this study, sine analysis results have shown deficiencies in comparison to CLA however, MMAC analysis results have been bounding

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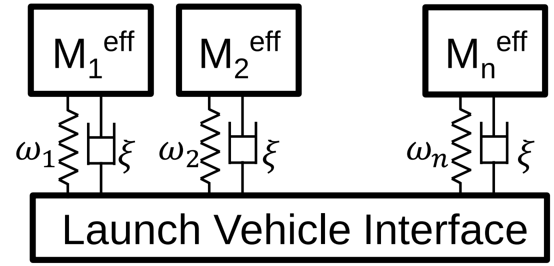
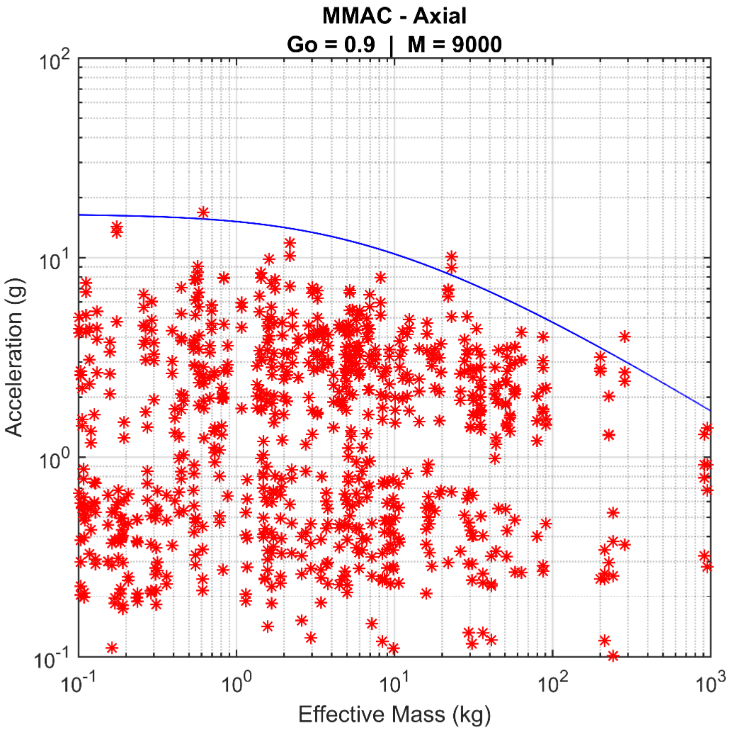
Background

MMAC Analysis

- Successfully implemented at JPL over the past 30 years for spacecraft launch loads for all JPL missions.
- Innovative extension of the PMAC loads analysis method to modal models of spacecraft structure.
- MMAC is based on the principle that the acceleration response of a base driven system is inversely proportional to the square root of mass.
- Each mode is treated as a single DOF system fixed at Spacecraft to LV interface with some effective mass
- MMA-Curve bounds the magnitude of the modal accelerations as a function of effective mass of each mode





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Background

MMAC Analysis

- MMAC Advantages
  - *Quick turnaround:*
    - Load analysis for a payload are done in few days
  - *Large output request:*
    - Possible to output loads for the entire payload model
  - *Launch Vehicle Models*
    - Launch vehicle models and forcing functions are not required

- Considerations
  - *Bounding Loads:*
    - Provides bounding loads for the low frequency launch dynamic environments (<100 Hz) – not a simulation
  - *Not intended to replace the CLA*
    - Intended to support structural design between CLA cycles

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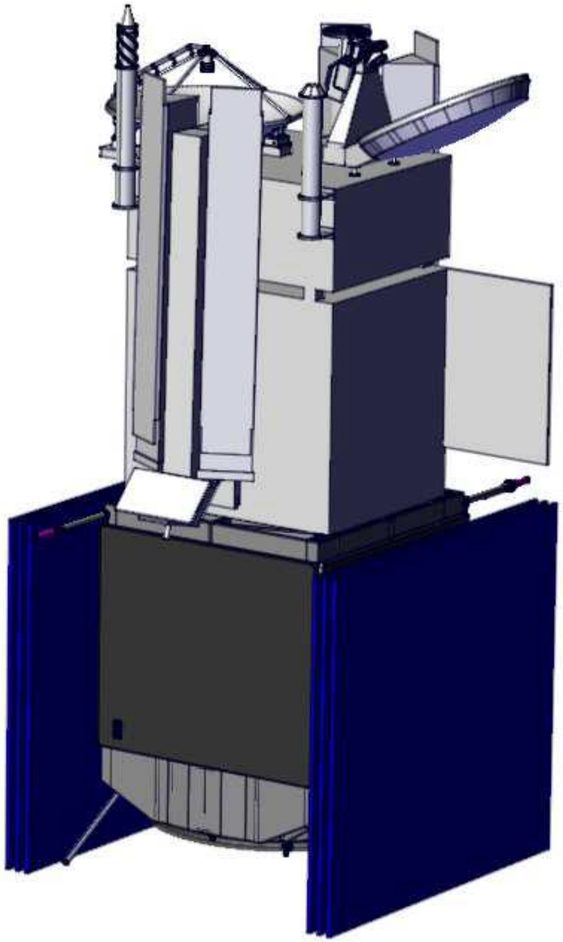
Mission

- Joint project between JPL and an international partner
- Sine analysis are required for estimating the low frequency launch loads
- Mission type: Earth orbiting Satellite
- Mass: ~ 2000 kg
- Launch Vehicle
  - *Space X Falcon 9*
- This study uses Hurty/Craig-Bampton model of the spacecraft (CLA model)



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MMAC Analysis

Inputs

- Inputs
  - *FEM of Payload:*
    - To get the constraint modes, inertia relief modes , fixed-base normal modes
  - *Payload to Launch Vehicle Interface Accelerations:*
    - Dynamic and mean components
    - Tuned to bound the CG load factors
  - *Modal Mass Acceleration Curve:*
    - CLA results from the current project or previous projects with similar configurations and launch vehicle

$$Accelration\ Bound\ Estimate$$

$$|\ddot{x}(t)| =$$

$$= \sum_{r=1}^{6} |\phi_r^{cm} \ddot{x}_r^{mean}| + \sqrt{\sum_{r=1}^{6} \left(\phi_r^{cm} \ddot{x}_i^{dyn}\right)^2 + \sum_{s=1}^{n} (\phi_s^{nm} \sqrt{m_s^{eff}}\, \ddot{q}_s^{MMAC})^2}$$

$\ddot{x}_r^{mean}$ = P/L to L/V interface accel. (mean)

$\ddot{x}_r^{dyn.}$ = P/L to L/V interface accel. (dynamic)

$\sqrt{m_s^{eff}}$ = Effective mass, square-rooted

$\ddot{q}_s^{MMAC}$ = Modal Mass Acceleration

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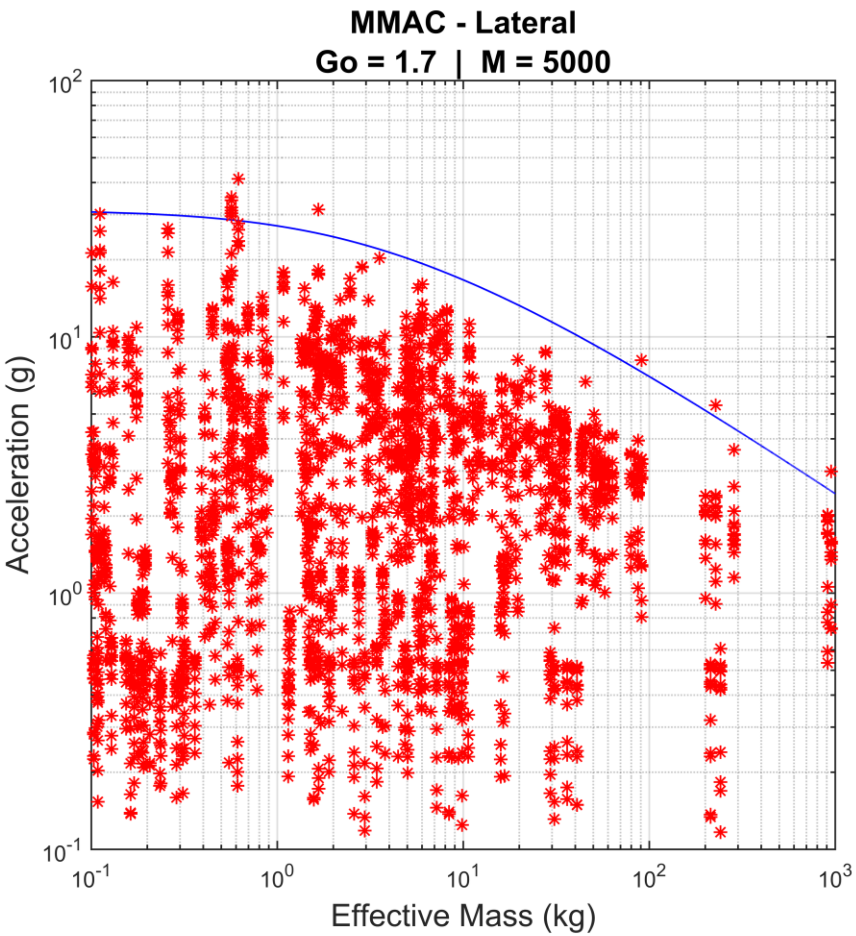
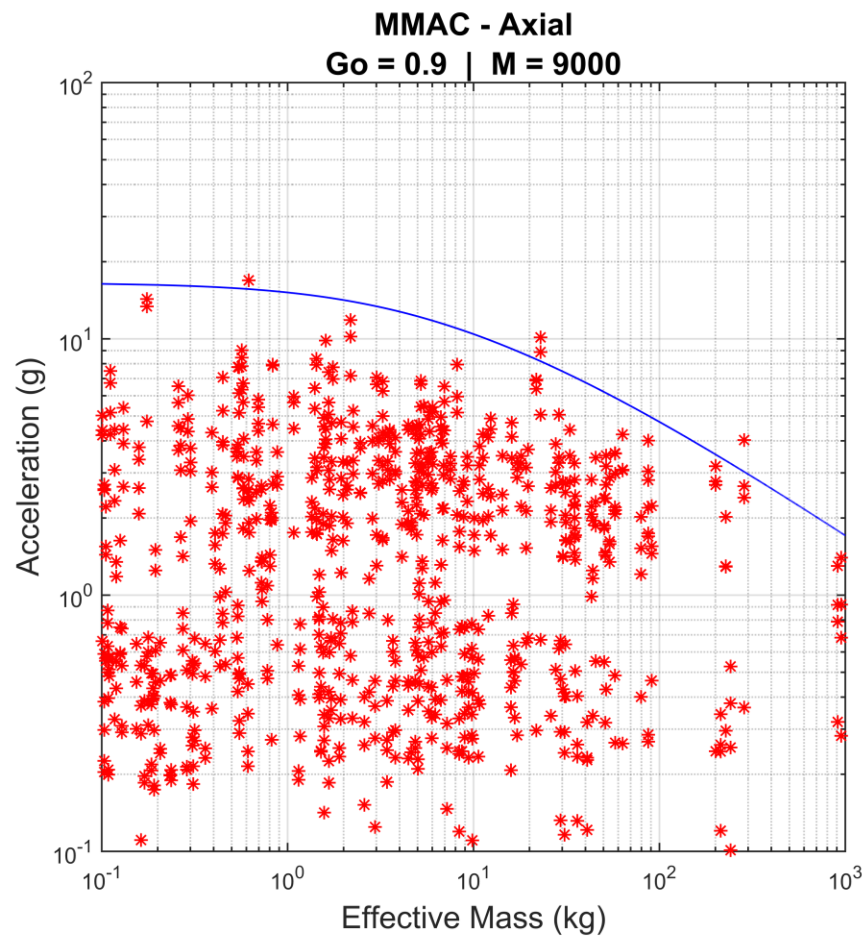
MMAC Analysis

Parameters





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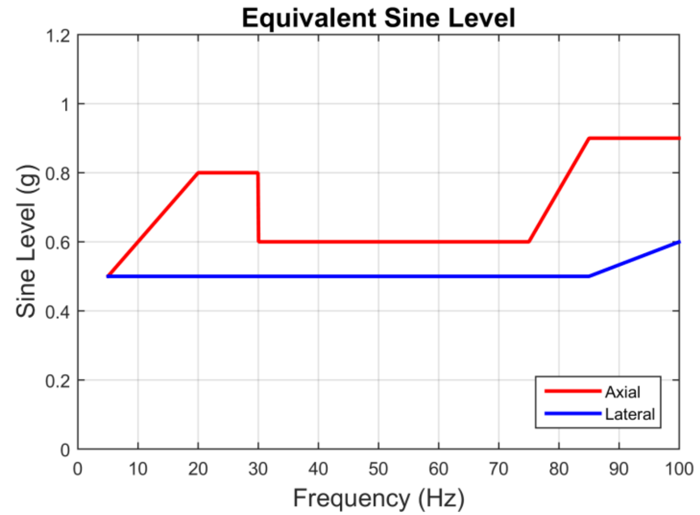
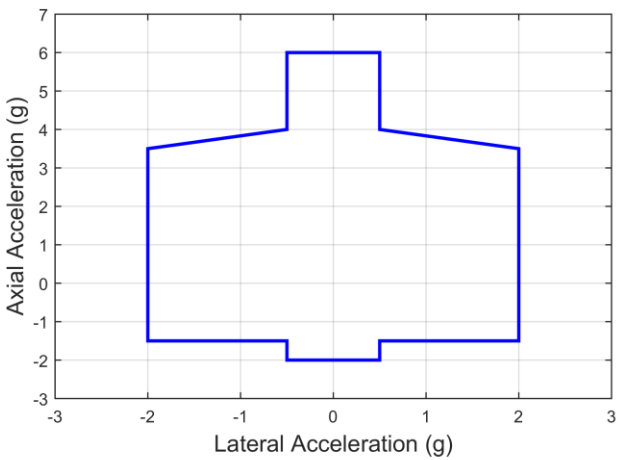
Sine Analysis

Summary

- SpaceX Falcon 9 Version 1.1
- 2% Damping
- Sine Environment
  - *Planner's guide*
- Force limiting
  - *CG Load Factors (higher of the CLA and the value given in the planner's guide)*
  - *2.5 g for the lateral case*





Axial

Freq. (Hz)	Accl. (g)
5	0.5
20	0.8
30	0.8
30	0.6
75	0.6
85	0.9
100	0.9

Lateral

Freq. (Hz)	Accl. (g)
5	0.5
85	0.5
100	0.6

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CLA Analysis
Summary

- Early Coupled Loads Analysis
  - *Falcon 9, Version 1.1*
  - *1% Damping*
  - *Frequency Range: f <100 Hz*
  - *Only acceleration results available*
  - *Standard suite of Falcon 9 CLA events*
  - *Dynamic Uncertainty Factor: 1.5*
  - *Static Uncertainty Factor: 1.0*

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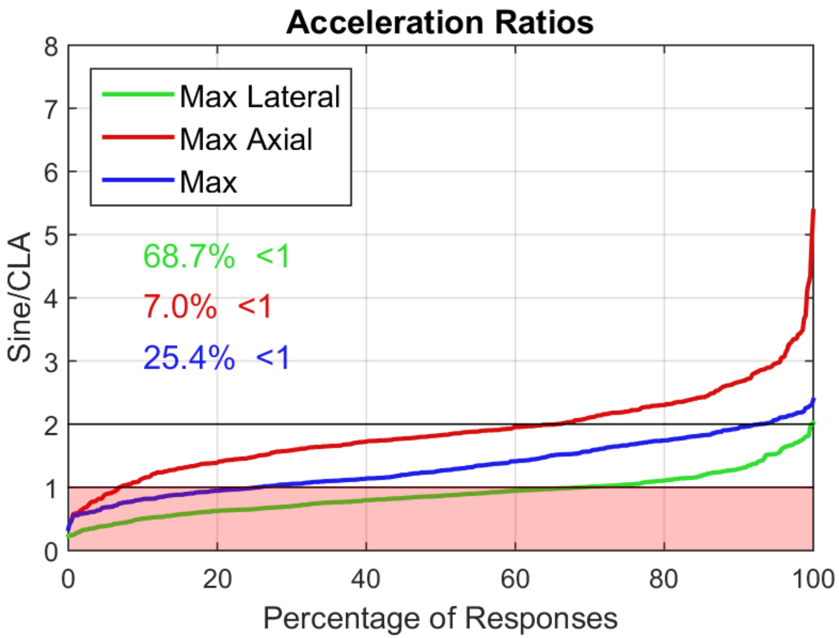
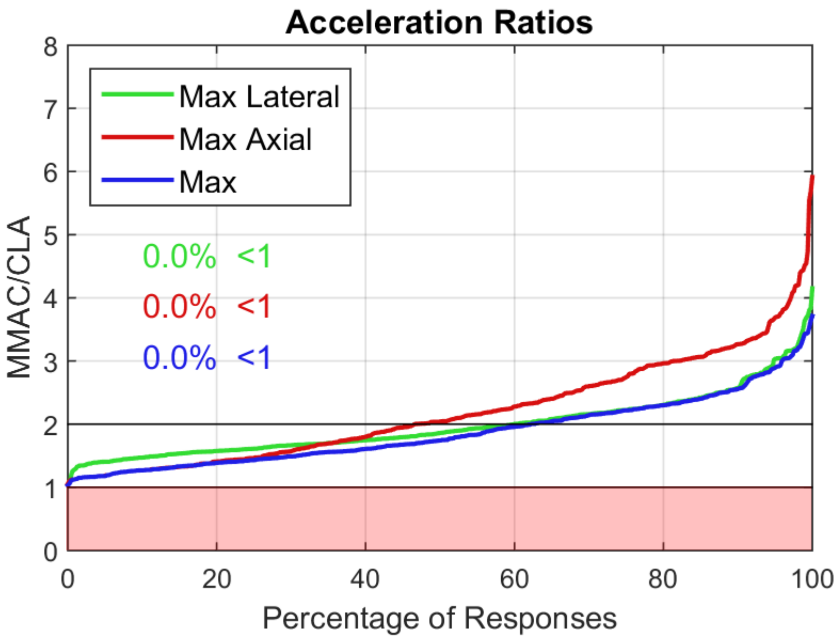
CLA Coverage

Sine vs MMAC

Sine vs CLA



MMAC vs CLA



- Sine results are deficient by 68.7% in the lateral case, 7% in the axial case, and 25.4 in the overall maximum case
- MMAC provides full coverage for all three cases without excessive conservatism

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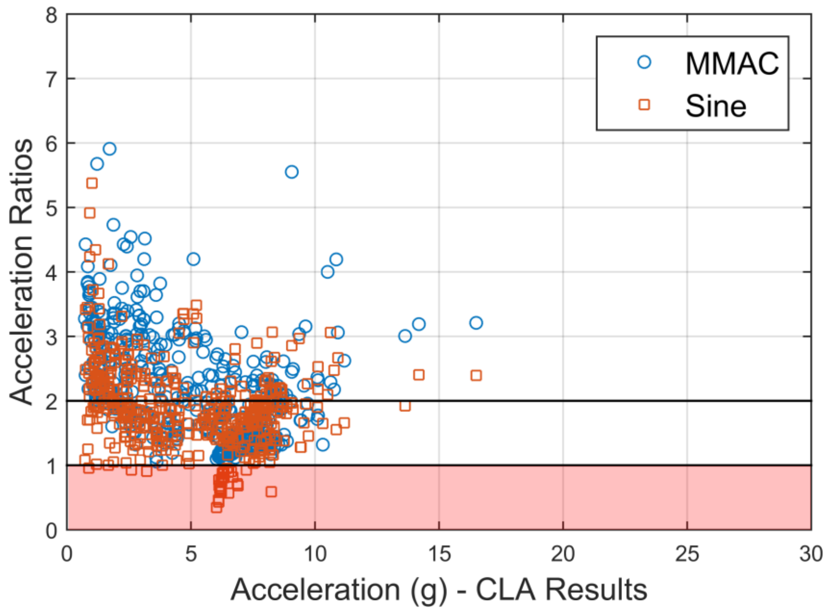
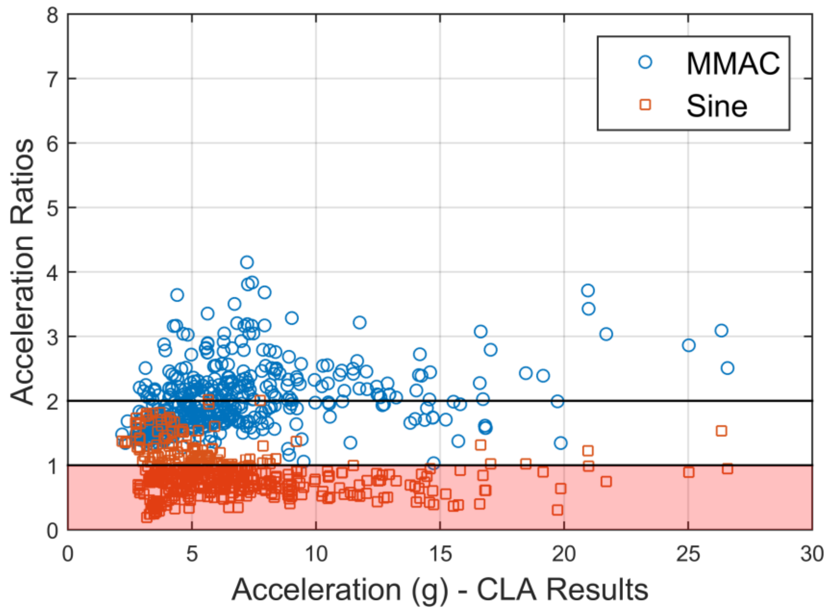
CLA Coverage

Sine vs MMAC

Axial



Lateral



- Deficiencies are observed across the entire range of acceleration values

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Conclusions

- Sine analysis showed notable deficiency when compared against the CLA accelerations in this example
  - *Sine environment is not representative of the actual flight environment and may be the source of the deficiencies*
    - Sine waveform is not representative of the actual acceleration time histories at the SC to LV interface
    - Sine is driven in only one DOF; actual flight environment drives all six DOFs simultaneously
    - Sine primarily drives a single mode; actual flight environment drives multiple modes at once
    - Sine capture only the dynamic component of interface acceleration; it does not capture the steady-state acceleration.
  - *For design purposes the higher result from the two analyses (CLA and sine analysis) should be used*

- MMAC provided a full coverage of the CLA results and does not have the shortcoming identified with the sine environment
  - *MMAC analyses is more representative of the flight environment than sine*

- Future Work
  - *Comparison of loads data in addition to the accelerations*
  - *Data comparison from other missions: SMAP, M2020, …*

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Thank you

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Backup Slides

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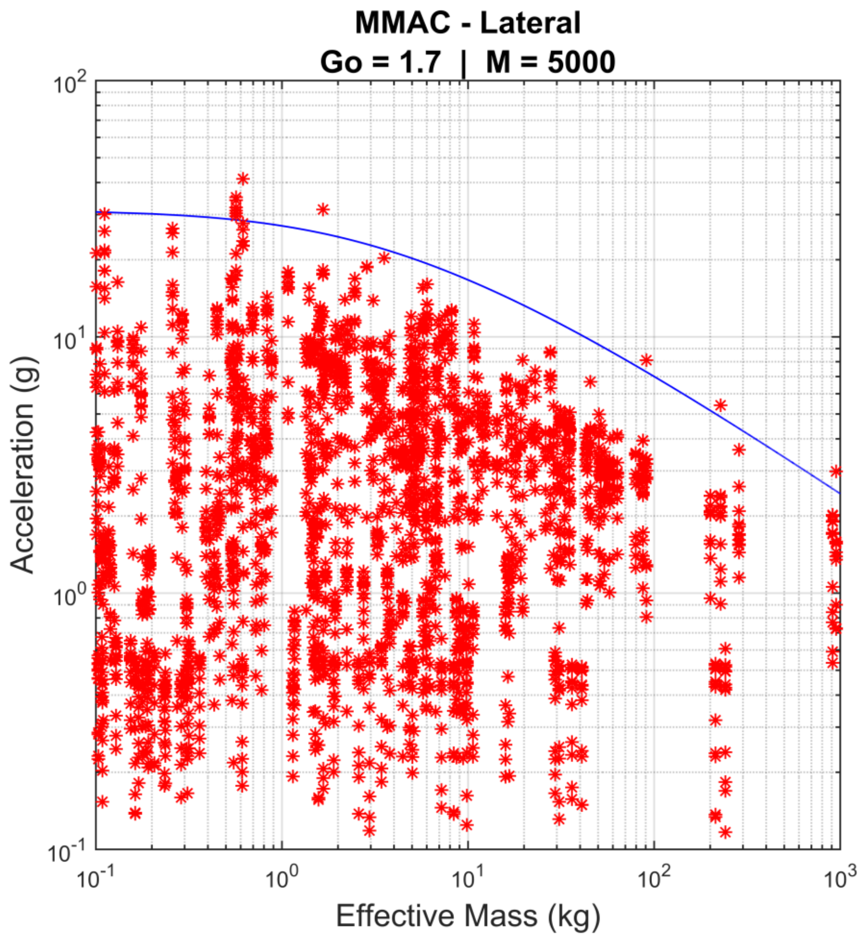
MMAC Analysis

Equation



$$MMAC(m) = \frac{Go}{\sqrt{\frac{m}{M} + \left(\xi_{sc} + \xi_{lv}\right)^2}} e^{\frac{-\alpha}{\tan(\alpha)}}$$

$$\alpha = Tan^{-1}\left(\frac{\sqrt{\frac{m}{M}}}{\xi_{sc} + \xi_{lv}}\right)$$

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MMAC Analysis

Summery

Max Lateral

	Mean	Dynamic
Tx	0.0	1.5
Ty	0.0	1.5
Tz	2.0	0.25
Rx	0.0	0.0
Ry	0.0	0.0
Rz	0.0	0.0

G_o = 1.7
S_w = 5000 lbf
Fact = 1.0
F_{max} = 100 Hz
Damping = 1%

Max Axial

	Mean	Dynamic
Tx	0.0	0.0
Ty	0.0	0.0
Tz	5.0	0.8
Rx	0.0	0.0
Ry	0.0	0.0
Rz	0.0	0.0

G_o = 0.9
S_w = 9000 lbf
Fact = 1.0
F_{max} = 100 Hz
Damping = 1%

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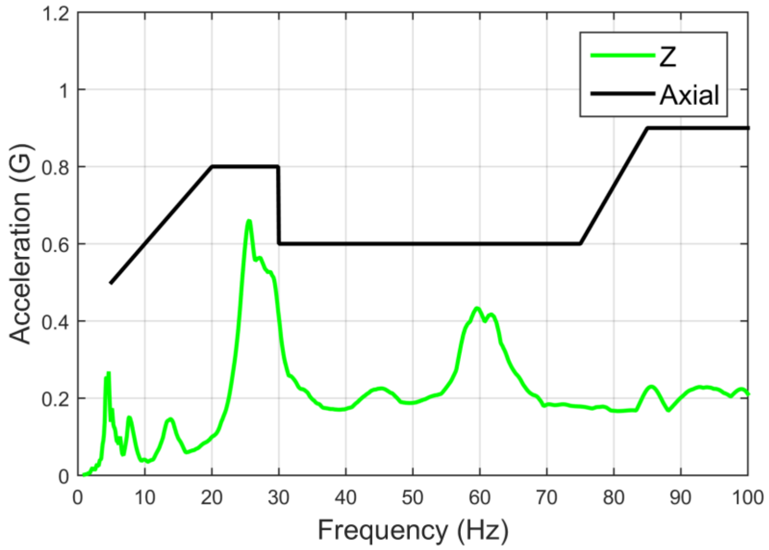
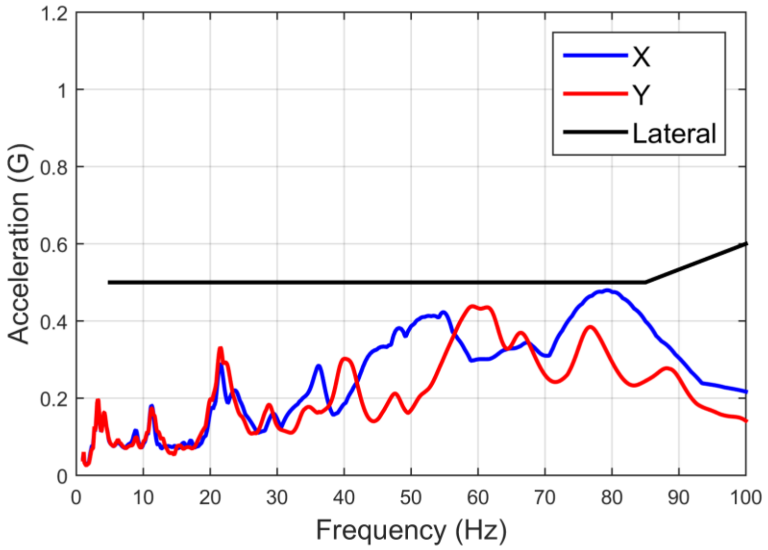
Interface Equivalent Sines from CLA Analysis

Compared with Sine Input Levels

Axial



Lateral



- Sine input levels cover the equivalent sines from CLA analysis

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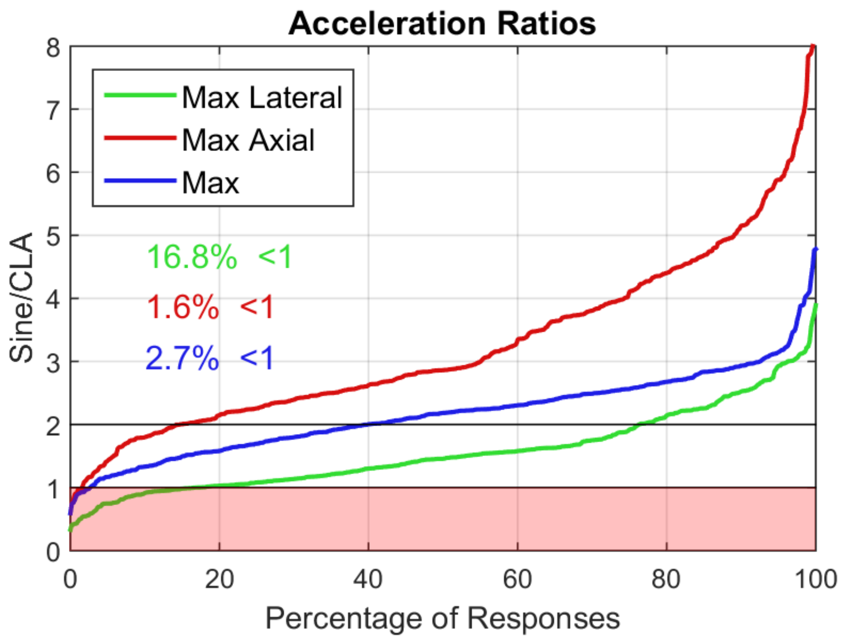
CLA Coverage

Sine vs MMAC

<u>Sine vs CLA</u>



- Using 1% damping significantly improves the coverage but deficiencies are still observed in all three cases
  - *Max Lateral : 16.8%*
  - *Max Axial : 1.6%*
  - *Max : 2.7%*

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